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Modeling and analysis of smoothly diffused vertical cavity surface emitting lasers

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ABSTRACT

Inter-diffusion in a 850 nm AlGaAs/GaAs top-emitting oxide-confined vertical-cavity surface-emitting laser (VCSEL) has been modeled and analyzed. Some important VCSEL parameters such as, the threshold gain, relative confinement factor, and the effective cavity length have been derived as a function of diffusion length and were found to reliably describe intermixing in VCSELs. It has been shown that inter-diffusion in VCSELs during typical molecular beam epitaxy (MBE) and metal-organic vapor-phase deposition (MOCVD) growth conditions is negligible and has no effect on a various range of VCSEL parameters. The model reveled that the VCSEL reflectivity spectra remains roughly unchanged for diffusion lengths of up to 16 nm, however, it is associated with a very small resonance shift and a decrease in the band width. The VCSEL threshold gain was found to increase noticeably at small diffusion lengths. The error-function solution to the diffusion equation as presented in the model could be adapted as a new compositional grading scheme in VCSELs. This newly proposed compositional grading scheme could be controlled during VCSELs growth and/or by post-growth thermal treatment.

1. Introduction

Vertical-Cavity Surface-Emitting Lasers (VCSELs) offer several advantages over other semiconductor lasers, such as the Edge-Emitting Lasers (EEL), due to their unique properties of emitting light perpendicular to the wafer surface, wafer scale fabrication and testing, small size, low cost and others [1]. These distinct features made VCSELs attractive light sources in numerous applications including, high speed data networks [2], optical interconnects [3], and many others.

Structurally VCSELs are relatively simple devices made of a gain medium placed in the center of an optical cavity embedded between two highly reflective mirrors called the top and bottom distributed Bragg reflectors (DBRs). The two DBRs form the optical feedback through which the current is injected. However, VCSELs growth and fabrication require a very sophisticated and precise control over the so many electrical and optical parameters, such as their DBRs reflectivity, resonance emission wavelength, their threshold current and gain, and many others, governing the realization of a reliable and high performance device. The precise tuning, control, and optimization over VCSELs optical and electrical requirements are often contradictory. These conflicting requirements have widely been the subject of extensive theoretical and experimental research in the basic physics governing the operating principles of VCSELs. For instance, several compositional grading schemes for efficient current injection through the top and bottom DBRs have been proposed [4–6].

Inter-diffusion of atoms across semiconductor hetero-interfaces has captured the attention of some research groups to study and investigate its effect in VCSELs. Indeed, intermixing of atoms across VCSELS DBRs has been shown to reduce their serial resistance for efficient current injection [7]. Impurity-induced intermixing in VCSELs has been reported to be a simple yet effective method for suppressing unwanted excitation of higher-order transverse modes [8]. Zhang et al. [9] have reported that a significant loss in a AlGaAs/GaAs VCSELs grown by metal-organic vapor-phase epitaxy (MOVPE) is due to doping-enhanced inter-diffusion during growth, furthermore, the authors suggested that a MBE growth might have an advantage in this respect since it usually uses a low growth temperature. Kink-free current-light output with threshold currents of about 2.4 mA of a 850 nm AlGaAs/GaAs VCSEL utilizing Si-implantation induced disordering has been demonstrated by Fang et al. [10], however, the authors gave no information about their annealing conditions. Recently, it has been reported that the intermixing of the AlAs layers is a useful techniques for controlling

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the oxidation rate in oxide-confined VCSELs [11]. Despite the fact that the effect of inter-diffusion in VCSELs and its integral parts (the DBRs) has been studied extensively, virtually little has been done to theoretically model its effect.

In this paper, a theoretical model is proposed and used to simulate the effect of intermixing in VCSELs. Results are presented showing that inter-diffusion has roughly no effect and can be considered negligible during MBE or MOVCD growth of AlGaAs/GaAs VCSELs. Post-growth thermal annealing and hence inter-diffusion is shown to affect differently a range of important VCSEL parameters. The model could serve as an analytical and design tool, not only to study inter-diffusion in VCSELs, but also as a new compositional grading method that can be controlled and achieved during VCSELs growth and/or by post-growth thermal processing.

2. Theoretical basis and model

2.1. Device description and design parameters

The device considered for modeling and analysis is a generic 850 nm GaAs/AlGaAs top emitting oxide-confined VCSEL grown on GaAs substrate. Fig. 1 shows an overall schamatic diagram of the considered VCSEL. From a structural point of view the considered VCSEL is roughly similar to that used by Wei-Choon et al. [12]. The device active region is a single 10 nm GaAs quantum well (QW) sandwiched between top and bottom $Al_xGa_{1-x}As$ barriers (spacers or cladding layers). The Al and Ga concentrations in the barriers required to achieve the desired 850 nm emission wavelength are obtained by numerically solving the 1D time-independent Schrödinger wave equation for a single GaAs QW in infinitely thick AlGaAs barriers using the shooting method. The 300 K QW n = 1 electron to heavy-hole transition energy (the 850 nm VCSEL emission wavelength) was calculated using the Pollak [13] relationship for the $Al_xGa_{1-x}As$ material system as given in Eq. (1).

$$E_g(x) = 1.424 + 1.34x(eV) \quad (1)$$

where x is the Al mole fraction value. A conduction to valence band offset ratio of 60:40 [14], an electron effective mass dependence on x of $0.067+0.083x$, and a heavy-hole effective mass of 0.83 [15] were used. These parameters were fitted into Schrödinger equation which was solved for a range of Al mole fraction values (x) to determine the required Al and Ga in the barriers at which the VCSEL emission wavelength occur. It has been calculated that the 850 nm VCSEL emission occur at an Al mole fraction value of $Al=0.22$ (please see Fig. 2), thus, the $Al_{0.22}Ga_{0.78}As$ material system was used as the QW barriers.

The thickness of the two spacers (barriers) and the active region are designed to form a $\approx 1.5\lambda$ cavity for optical and carriers confinement. The optical cavity is embedded between two $\lambda/4$ $Al_{0.98}Ga_{0.02}As$ layers for oxidation purpose. The cavity optical feedback is realized by 20 and 28 periods top and bottom $\lambda/4$ $Al_{0.1}Ga_{0.9}As/Al_{0.9}Ga_{0.1}As$ DBRs, respectively.

Fig. 1. An overall schematic illustration of the VCSEl structure used for modeling and analysis. The VCSEL consists of 20 and 28 periods top and bottom DBRs respectively, made of $\lambda/4\,Al_{0.1}Ga_{0.9}As/Al_{0.9}Ga_{0.1}As$(Light and dark blue). A $\lambda/4\,Al_{0.98}Ga_{0.02}As$ layers for oxidation (dark yellow), two top and bottom $Al_{0.22}Ga_{0.78}As$ barriers (dark green), and a 10 nm GaAs QW (red), grown on GaAs substrate.

2.2. Theoretical model

For modeling and analysis it is initially assumed that the grown layers forming the device are perfectly abrupt in compositions and thicknesses. The diffusion process considered is based on thermal-induced smooth changes in the compositions and thicknesses of the layers forming the VCSEL during growth or post-growth thermal annealing. Theoretically such changes can be modeled by solving Fick's second law of diffusion (Eq. (2)).

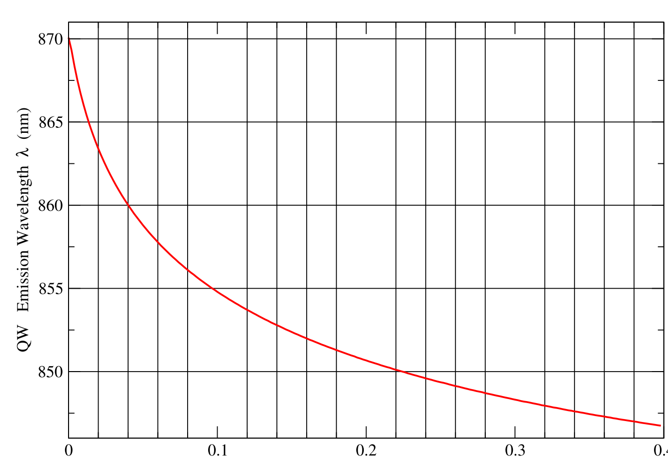

Fig. 2. The calculated n = 1 electron to heavy-hole transition wavelength as a function of Al mole fraction value (x) for a single 10 nm GaAs QW in thick $Al_xGa_{1-x}As$ barriers. The 850 nm VCSEL resonance wavelength is obtained at the Al calculated value of x=0.22. The QW and barriers were assumed to be perfectly abrupt in composition.

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